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LIFE vs. LWR: End of the Fuel Cycle

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The Need for Energy Drives the Nuclear Option

The worldwide energy consumption in 2003 was 421 quadrillion Btu (Quads), and included 162 quads for oil, 99 quads for natural gas, 100 quads for coal, 27 quads for nuclear energy, and 33 quads for renewable sources. The projected worldwide energy consumption for 2030 is 722 quads, corresponding to an increase of 71% over the consumption in 2003. The projected consumption for 2030 includes 239 quads for oil, 190 quads for natural gas, 196 quads for coal, 35 quads for nuclear energy, and 62 quads for renewable sources [International Energy Outlook, DOE/EIA-0484, Table D1 (2006) p. 133]. The current fleet of light water reactors (LRWs) provides about 20% of current U.S. electricity, and about 16% of current world electricity. The demand for electricity is expected to grow steeply in this century, as the developing world increases its standard of living. With the increasing price for oil and gasoline within the United States, as well as fear that our CO_2 production may be driving intolerable global warming, there is growing pressure to move away from oil, natural gas, and coal towards nuclear energy. Although there is a clear need for nuclear energy, issues facing waste disposal have not been adequately dealt with, either domestically or internationally. Better technological approaches, with better public acceptance, are needed.

Issues Facing Light Water Reactor Fuel Cycles

Nuclear power has been criticized on both safety and waste disposal bases. The safety issues are based on the potential for plant damage and environmental effects due to either nuclear criticality excursions or loss of cooling. Redundant safety systems are used to reduce the probability and consequences of these risks for LWRs. LIFE engines are inherently subcritical, reducing the need for systems to control the fission reactivity. LIFE engines also have a fuel type that tolerates much higher temperatures than LWR fuel, and has two safety systems to remove decay heat in the event of loss of coolant or loss of coolant flow. These features of LIFE are expected to result in a more straightforward licensing process and are also expected to improve the public perception of risk from nuclear power generation, transportation of nuclear materials, and nuclear waste disposal.

Waste disposal is an ongoing issue for LWRs. The conventional (once-through) LWR fuel cycle treats unburned fuel as waste, and results in the current fleet of LWRs producing about twice as much waste in their 60 years of operation as is legally permitted to be disposed of in Yucca Mountain. Advanced LWR fuel cycles would recycle the unused fuel, such that each GWe-yr of electricity generation would produce only a small waste volume compared to the conventional fuel cycle. However, the advanced LWR fuel cycle requires chemical reprocessing plants for the fuel, multiple handling of radioactive materials, and an extensive transportation network for the fuel and waste. In contrast, the LIFE engine requires only one fueling for the plant lifetime, has no chemical reprocessing, and has a single shipment of a small amount of waste per GWe-yr of electricity generation. Public perception of the nuclear option will be improved by the reduction, for LIFE engines, of the number of shipments of radioactive material per GWe-yr and the need to build multiple repositories. In addition, LIFE fuel requires neither enrichment nor reprocessing, eliminating the two most significant pathways to proliferation from commercial nuclear fuel to weapons programs.

Yucca Mountain Repository

The capacity of the first geological repository for high-level radioactive waste in the U.S. is statutorily limited to 70,000 metric tons (MT) of initial heavy metal equivalent by the Nuclear Waste Policy Act of 1982 as amended. The License Application (LA) for the Yucca Mountain repository allocates 63,000 MT of this capacity to the disposal of commercial spent nuclear fuel (CSNF), with the remaining 7,000 MT allocated to vitrified defense high-level radioactive waste (HLW glass) and DOE spent fuel. The ultimate physical capacity of a repository at Yucca Mountain could be significantly higher (at least 120,000 MT and likely considerably higher) than the statutory limit. For simplicity in this report, we define a "Yucca Mountain Equivalent" (YME) repository as one that can accommodate the equivalent of 63,000 MT of heavy metal.

In testimony to Congress in late July 2008, the Department of Energy (DoE) announced that the cost for the Yucca Mountain Repository has increased from the original life-cycle cost of $58 billion to more than $90 billion [DOE Testifies, Yucca's Costs Doubled, New Estimates of More Than $90 Billion, Nuclear Waste News, Capitol Press LLC, Vol. 28, No. 15, July 21, 2008, p. 1]. It should be noted that both life-cycle costs quoted above are for waste volumes larger than the statutory limit. The cost increase is due to factors including the cost of temporarily storing the current inventory of spent nuclear fuel, as well as escalating costs for construction and procurement of materials for the engineered barrier system of the repository. Given the increasing cost for geological disposal and strong public and state governmental opposition, any nuclear power-generation option that can increase the quantity of electrical energy serviced by a facility such as Yucca Mountain, thereby decreasing the need for a larger number of future repositories, should be welcome.

The use of LIFE engines for the generation of electricity has significant benefits in terms of increasing the capacity and lifetime of a geologic nuclear waste repository, while simultaneously improving the societal risk/benefit ratio of such a facility. To frame this discussion, we have analyzed the volumetric, radiological, and thermal implications for the back end of the fuel cycle for the case of a LIFE engine fueled initially with 40 MT of depleted uranium (DU), and operated continuously to burn-ups of 95%, 99%, and 99.5% FIMA (fissions per initial metal atom). Such an engine has a thermal output of approximately 2 GWt at steady state, and by the time the fuel reaches a burnup of 99% FIMA, the engine has generated in excess of 44 GWe-net·yr of electricity.

Conventional LWR Fuel Cycle Requires Many Repositories

The International Atomic Energy Agency (IAEA) has published the world wide inventory of reactors and spent nuclear fuel [K. Fukuda, W. Danker, J. S. Lee, A. Bonne, M. J. Crijns, IAEA Overview of Global Spent Fuel Storage, IAEA-CN-102/60, Department of Energy, International Atomic Energy Agency, Vienna, Austria, Table I]. These data are summarized in Table 1. The LWRs around the word have already generated enough spent nuclear fuel to fill 3.9 Yucca Mountain repositories. In North America alone, the current inventory of spent fuel would fill 1.7 Yucca Mountain Equivalent repositories.

Table 1 – Worldwide base of installed light water reactors (LWRs) showing generating capacity and current inventory of spent fuel. One "Yucca Mountain Equivalent" is assumed to have the capacity to accept 63,000 MT of heavy metal (HM).

	LWRs	LWR Generating Capacity	Total SNF in storage	Yucca Mtn. Equivs. Needed	Cost for YMEs
	#	GWe	kT HM	#	U.S. $B
Western Europe	146	126	72	1.14	103
Eastern Europe	67	46	34	0.54	49
N. America	124	112	105	1.67	150
Asia & Africa	104	75	33	0.52	47
World	**441**	**359**	**244**	**3.87**	**348**

Comparing the End of the Fuel Cycle for LIFE & LWR Systems

The emphasis for LIFE engine development design is focused on hot-spot (HS) ignition with a green laser (2ω) and chamber geometry similar to that used in the National Ignition Facility (NIF). Most work to date has assumed that the LIFE Engine would be sized to produce approximately one gigawatt of electrical power (1 GWe). Most of the repository comparisons in this report are based upon this capacity. However, emerging systems and cost models at LLNL show that there is an economy of scale that leads to an economic optimum. As the technology evolves, economic forces may drive more mature designs to plants capable of producing two gigawatts of electrical power (2 GWe) or greater. Similar scaling effects have been observed with other large power-production technologies. This optimum is illustrated in Figure 1.

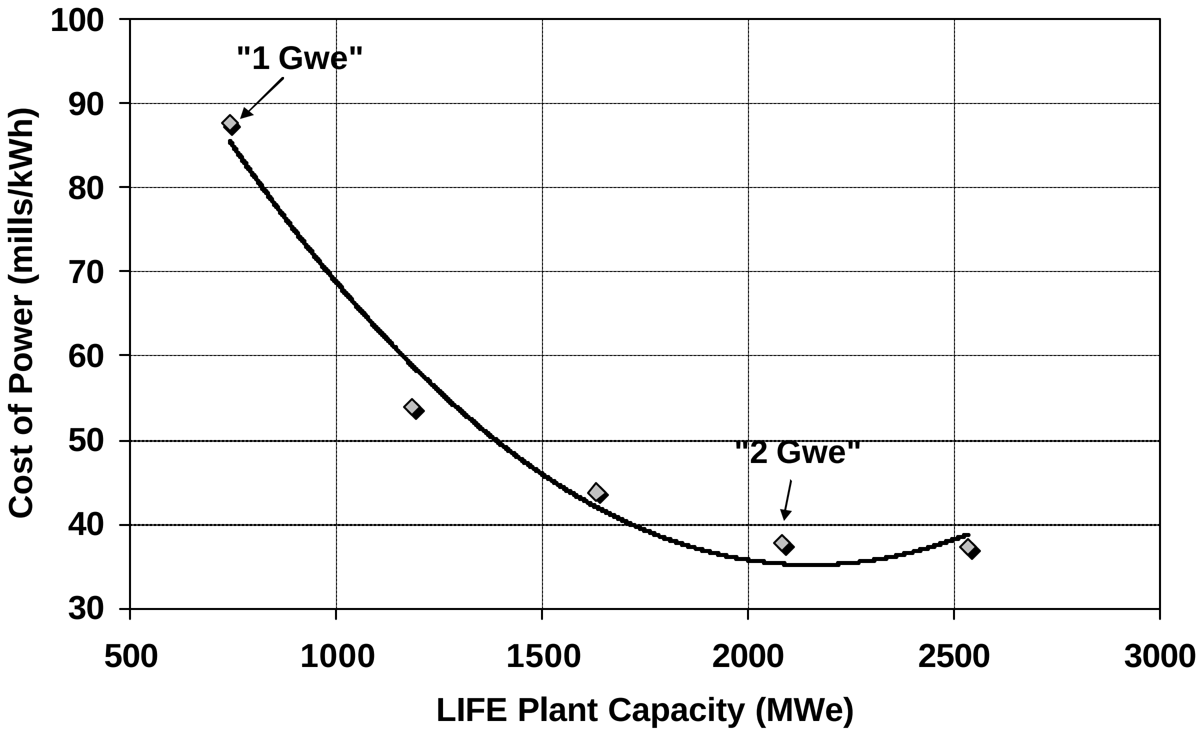


Figure 1 – Economy of scale for LIFE plants assuming NIF-type hot-spot ignition, and the burning of TRISO fuel with natural or depleted uranium kernels.

As shown in Table 2, the nominal 1-GWe LIFE plant, which has a net electrical power output of 739 MW, will require an initial fuel charge of 40 MT of natural or depleted uranium metal, while a nominal 2-GWe plant would have a 107 MT charge and a net electrical power output of 2081 MW. The uranium will be converted to uranium oxycarbide (UOC) and used to form the kernels at the core of enhanced TRISO particles (~ 1 mm diameter), engineered to enable relatively high burn-up. Several thousand TRISO particles will then be embedded in a larger pebble (2-cm diameter). Approximately 15 or 41 million of these pebbles would be required for the nominal 1-GWe or 2-GWe LIFE plants, respectively. The engines have nominal lifetimes of ~50 full power years (the time required to reach 99.5% FIMA), by which time the 1-GWe engine will have generated about 44 GWe-net·yr of electricity, while the 2-GWe plant would have generated about 133 GWe-net·yr. Both size engines would produce net electrical power at a rate of 1.1 - 1.2 GWe-net·yr/MT. Once spent, and after a minimum 5-year cooling period (see below) the fuel pebbles would be loaded into standard transportation, aging and disposal (TAD) containers developed for the Yucca Mountain repository (the TAD material may be different for spent LIFE fuel. Assuming a 60% packing fraction of the pebbles in the TADs, the spent fission fuel from the 1- and 2-GWe LIFE engines would require 10.5 or 28 TADs, respectively.

Although LIFE engines would be introduced into the market gradually, it is useful to make a direct comparison of the repository capacity required to service a hypothetical worldwide fleet of LIFE engines with a total electrical generating capacity equivalent to the current worldwide fleet of LWRs. This estimate, which is based on the heavy metal mass flows given in Table 8, is shown in Table 3. This comparison shows that use of a fleet of 2-GWe LIFE engines with the current worldwide electrical generation capacity would reduce the current worldwide need for repository capacity from 3.9 YMEs to 0.23 YME. Assuming that 1 YME costs $90 billion, as announced by the United States Department of Energy in late July 2008, the cost differential is calculated to be approximately $327 billion.

Table 2 - Generation of LIFE SNF by hypothetical LIFE plants fueled with depleted uranium.

	2-GWe Engine	1-GWe Engine	
Net Electrical Power	2081	739	MWe
Fission Fuel Loading	107	40	MTHM
Burnup	99.5	99.5	% FIMA
Thermal Energy Generated	126,000	47,000	GWt·d
Net Electrical Energy	133	44	GWe-net·yr
Burn Duration	53	50	Years
Pebbles per Engine	41,171,120	15,391,073	
Pebbles per TAD Container	1,470,340	1,470,340	
TAD Containers per Engine	28	10.5	
Plant availability	90	90	Percent
Power per MT Fuel	1.2	1.1	GWe-net·yr/MT
Cost of Electrical Power	38	88	mils/kWh

Table 3 – Repositories that would required now, had the energy generated worldwide by LWRs been generated by a hypothetical fleet of 2-GWe LIFE engines. Compare with the current worldwide situation shown in Table 1.

	LIFE Engines	LIFE Generating Capacity	LIFE Total SNF	Yucca Mtn. Equivs. Needed	Cost for YMEs	Cost Differential LWR-LIFE
	#	GWe	kT HM	#	U.S. $B	U.S. $B
Western Europe	60	126	6.4	0.10	9.0	94
Eastern Europe	22	46	2.4	0.04	3.6	45
N. America	54	112	5.8	0.09	8.1	142
Asia & Africa	36	75	3.9	0.06	5.4	42
World	**172**	**359**	**18.4**	**0.29**	**26.1**	**322**

Note: The values in this table are based on 2.081 GWe for each LIFE engines; similar operating lifetimes; 107 MT of SNF from each LIFE engine; 63,000 MT per YME repository; and $90B cost per repository. The cost estimates in Tables 1 and 3 ignore the additional MT capacity included in the Yucca Mountain total system life cycle costs quoted. These tables also assume that the larger repository footprint and additional waste packages required for a LIFE repository (3.8 MT/WP vs 8.4 MT/WP for LWR waste) do not significantly affect the cost comparison.

In addition to the spent fission fuel, a complete accounting of the waste from a LIFE engine must also include other contaminated radioactive materials that require disposal as radioactive or hazardous waste or can be recycled for use in other LIFE engines. Because the mass of tungsten, steel and beryllium are comparable to that of the spent fission fuel, and because these materials are costly, a foundry for re-fabrication and recycle of these materials is required. It is anticipated that any of these materials that are not recycled will qualify for shallow land burial as low- or intermediate-level radioactive waste.

Table 4 – Other spent materials appearing during or at the end of the LIFE fuel cycle.

	LIFE					LWR
	Spent Fission Fuel	Spent First Wall	Spent Steel Chamber	Spent Be Multiplier	Spent Material Total	Spent Fission Fuel
	kT HM	kT W	kT ODS	kT Be	kT	kT HM
Western Europe	6	10	10	24	50	72
Eastern Europe	2	4	4	9	18	34
N. America	6	9	9	21	45	105
Asia & Africa	4	6	6	14	30	33
World	18	29	29	68	143	244

As shown in Table 8, a LIFE engine will discharge approximately 15-17 times less spent fuel, 300 times less Pu, and 50 times less transuranic elements (TRUs) than comparable LWRs per unit electrical energy produced, assuming a once-through fuel cycle for the LWRs. The smaller quantities of spent fuel are due to the high burnup in LIFE, which uses the same fuel long enough to extract almost all the available fission energy in it. Therefore, it is expected that the repository capacity and disposal costs will be smaller than for conventional LWRs, as demonstrated in Tables 1 and 3.

Radiological Considerations

Under current U.S. regulations, the performance of a repository is measured in terms of the average annual dose to the reasonably maximally exp osed individual (RMEI). The calculation of this quantity is dependent on the details of the timing and kinetics of the failure of waste packages, and the subsequent release and transport of radionuclides through the repository system and surrounding geologic environment. These processes are in turn dependent on the scenarios the repository, including seismic disruption, igneous disruption, human intrusion, and the nominal situation with none of these disruptions. Because of the differences in elemental transport rates through the environment, the radionuclides that account for the bulk of the radioactivity in nuclear waste are not, in general, the radionuclides that are predicted to contribute most to the dose to the RMEI. The total system performance assessment (TSPA) for the Yucca Mountain License Application (TSPA-LA) found the radionuclides listed in Table 5 are the ones responsible for the bulk of the dose attributable to the repository.

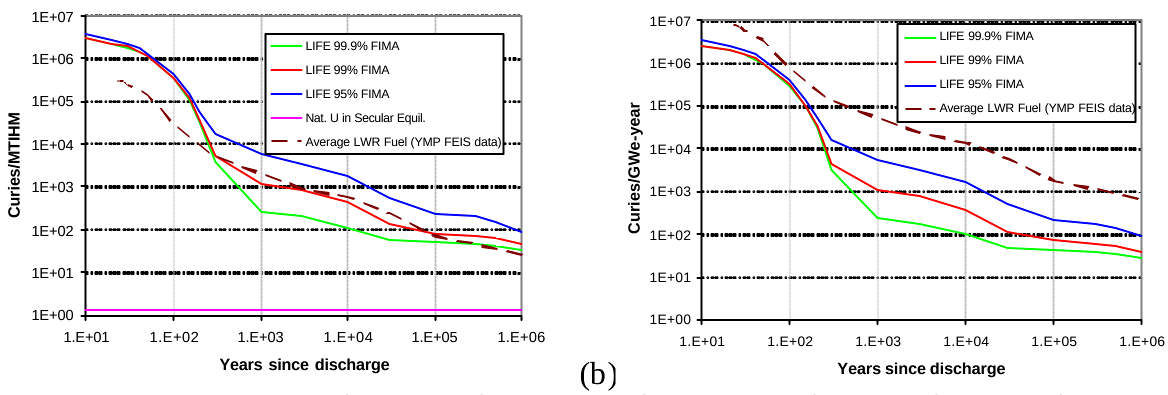
Table 5 -- Nuclides identified in the Yucca Mountain TSPA-LA as dominating the doses for different time periods from a Yucca Mountain repository

	< 10,000 years	10,000 to 100,000 years	100,000 to 1,000,000 years
Most important radionuclides overall	^{99}Tc, ^{14}C, ^{129}I, ^{239}Pu	^{239}Pu, ^{129}I, ^{226}Ra	^{226}Ra, ^{242}Pu, ^{237}Np
Other nuclides important for specific scenarios	^{240}Pu, ^{241}Am	^{79}Se, ^{99}Tc, ^{135}Cs, ^{237}Np, ^{240}Pu, ^{242}Pu	^{79}Se, ^{99}Tc, ^{135}Cs, ^{237}Np, ^{240}Pu, ^{242}Pu

The specific radioactivity of spent LIFE fuel (activity per MT of initial heavy metal) with 95%, 99%, and 99.9% FIMA is significantly higher than that of average LWR fuel for approximately 300 years after discharge (see Fig. 2a). The specific activity of LIFE fuel with a burnup of 95% FIMA remains above that of average LWR fuel for all times. Spent LIFE fuel with a burnup of

99% FIMA has a specific activity similar to that of average spent LWR fuel from about 300 years to 100,000 years post discharge, while the 99.9% FIMA LIFE fuel has a specific activity less than that of average LWR fuel from about 300 years to 100,000 years post discharge. At very long times (>300,000 years), the specific activities of the spent LIFE fuels for all three burnups are somewhat higher than that of average spent LWR fuel.

When normalized to the total electrical energy generated by the LIFE or LWR fuel, the radioactivity per-unit-energy-generated of spent LIFE fuel with burnup > 95% FIMA is always less than that of similarly normalized spent LWR fuel (Fig. 2b), suggesting that the benefit to hazard ratio of LIFE waste is significantly better than that of spent LWR fuel. Nevertheless, the spent fission fuel for a LIFE engine is a hazardous material that will require isolation from the biosphere for hundreds of thousands of years. Generation of electrical power by LIFE engines fueled with depleted uranium will not obviate the need for long-term geological repositories for the discharged waste, although the number of repositories will be much less than for conventional LWRs.

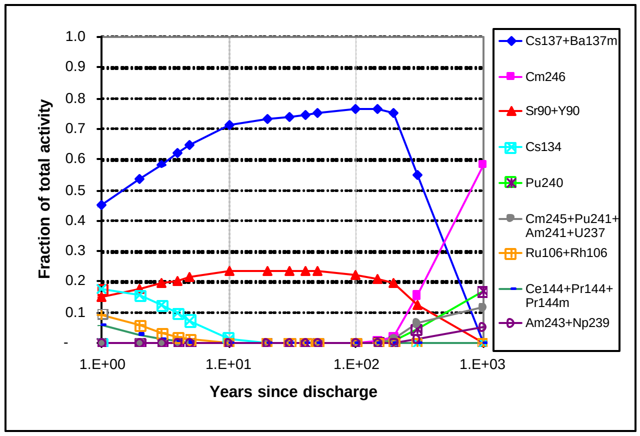


(a) (b)

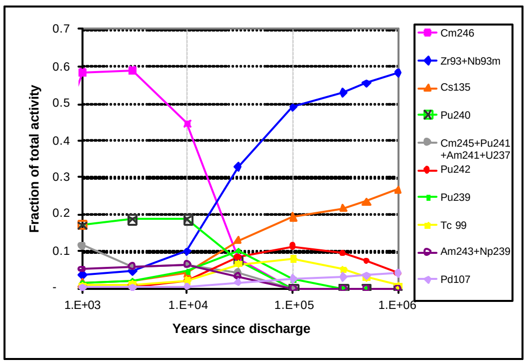
Figure 2 -- (**a**) Comparison of the specific activity of spent LIFE fuel as a function of time since discharge with that of average LWR fuel. For comparison, the specific activity of natural uranium in secular equilibrium with its daughter products is also plotted. (**b**) Activity of spent LIFE fuel normalized to the total energy generated by that fuel. For comparison, the similarly normalized activity of average LWR fuel is also plotted.

For decay times of less than ~300 years, the activity of spent LIFE fuel is dominated by short-lived fission products. Specifically, the activity of the waste (regardless of burnup) from the DU-fueled LIFE engine is dominated by the decay of the fission products (^{137}Cs + ^{137m}Ba, and ^{90}Sr + ^{90}Y) for the first few hundred years after discharge (Fig 3a). These are the same nuclides responsible for most of the activity of spent LWR fuel during this time period.

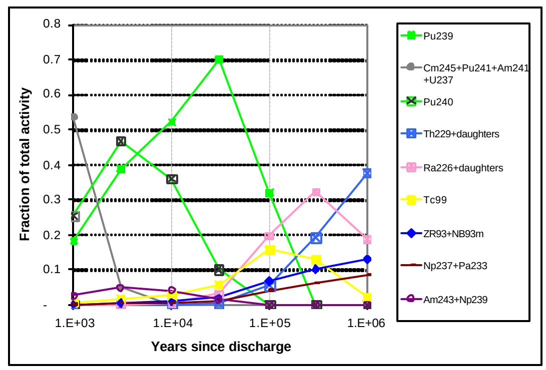
Between ~300 and a few tens of thousands of years (Fig 3b) decay of the actinides and their daughter products (^{246}Cm, ^{240}Pu) are the dominant sources of radioactivity in spent LIFE fuel. At times greater than ~20,000 years, fission products (the long-lived nuclides ^{135}Cs, ^{93}Zr + ^{93m}Nb, and ^{99}Tc) once again become the dominant source of radioactivity. The only actinide that contributes more than 5% of the total activity during the post-100,000-year time period is ^{242}Pu. LIFE waste differs substantially from average LWR spent fuel in terms of the isotopic makeup of the primary contributors to the activity after a few hundred years of decay. The activity in spent LWR fuel is dominated by ^{241}Am, ^{239}Pu, ^{240}Pu, ^{226}Ra (+ daughters), ^{229}Th (+ daughters), and ^{99}Tc (Fig 3c).



(a)



(b)



(c)

Figure 3 – (a) Fractional contribution of individual nuclides and decay chains in secular equilibrium to the total activity of 99% FIMA LIFE fuel for the period 1 to 1000 years post discharge. The figure includes all nuclides (or decay chains) that contribute more than 5% to the total activity at any time during this period. (b) Fractional contribution of individual nuclides (or decay chains in secular equilibrium) to the total activity of 99% FIMA LIFE fuel for the period 1000 to 1,000,000 years post discharge. (c) Fractional contribution of individual nuclides (or decay chains in secular equilibrium) to the total activity of average spent LWR fuel for the period 1000 to 1,000,000 years post discharge. The figure includes all nuclides (or chains) that contribute more than 5% to the total activity at any time during these periods.

An expanded list of radionuclides that includes high-activity nuclides present in LIFE waste that are not significant for spent LWR fuel, as well as nuclides contributing to a lesser extent to the calculated YMP dose, is given in Table 6. This table also lists the ratio of the specific activities of these nuclides in LIFE waste to the average activity in CSNF. For cases in which this ratio varies over time due to differential rates of in-growth of daughters, the table lists the maximum value between 300 and 1 MY after discharge. With the exception of ^{79}Se, ^{93}Zr, ^{129}I, ^{135}Cs, ^{242}Pu, and ^{246}Cm, all the radionuclides identified as being important in the Yucca Mountain TSPA-LA have lower specific activities in LIFE waste. (Projections of the ^{14}C and ^{36}Cl content of spent LIFE fuel are not yet available.)

One can make a conservative, zeroth-order assessment of how a Yucca-Mountain-like repository containing 63,000 MT of spent LIFE fuel would perform by using the ratios in Table 6 to scale the doses calculated in the Yucca Mountain TSPA-LA for each of the listed nuclides, and making reasonable assumptions for nuclides such as ^{244}Pu and ^{248}Cm, which are not included in the TSPA-LA. This calculation also assumes that LIFE waste packages and fuel degrade and release radionuclides at the same average rate as the waste considered in the TSPA-LA and that the additional space needed to accommodate the full 63,000 MT of LIFE waste is available. The result indicates that the doses from such a repository would be within a factor of ±4 of the doses calculated for the TSPA-LA, and well within the regulatory limits of the proposed NRC regulation for the long-term postclosure performance of a repository, even though the LIFE repository would contain the waste resulting from the generation of ~15-17 times the energy of the currently proposed Yucca Mountain case.

Table 6 – Activity ratios (specific activity in 99% FIMA LIFE waste divided by specific activity in average LWR spent fuel) of nuclides of importance in the Yucca Mountain TSPA- LA or that are present at significant levels in LIFE waste but were not considered in the TSPA-LA. The highest ratio that occurs between 300 and 1 MY after discharge is tabulated.

Nuclide	LIFE/LWR activity ratio		Nuclide	LIFE/LWR activity ratio
^{14}C	a		^{233}U	0.12
^{36}Cl	a		^{234}U	0.15
^{79}Se	3.5		^{235}U	0.00
^{93}Zr	8.3		^{236}U	0.15
^{99}Tc	0.60		^{238}U	0.01
^{126}Sn	0.06		^{237}Np	0.12
^{129}I	13		^{239}Pu	0.28
^{135}Cs	29		^{240}Pu	>0.5
^{226}Ra	0.14		^{242}Pu	5.1
^{227}Ac	0.00		^{244}Pu	b
^{229}Th	0.12		^{246}Cm	8100
^{230}Th	0.14		^{248}Cm	b
^{231}Pa	0.00			

[a]No data available for LIFE case. Existing burn calculations for LIFE do not include estimates of ^{14}C and ^{36}Cl production.
[b]Nuclide not present at significant levels in YMP inventory

Mitigating the Threat of Proliferation

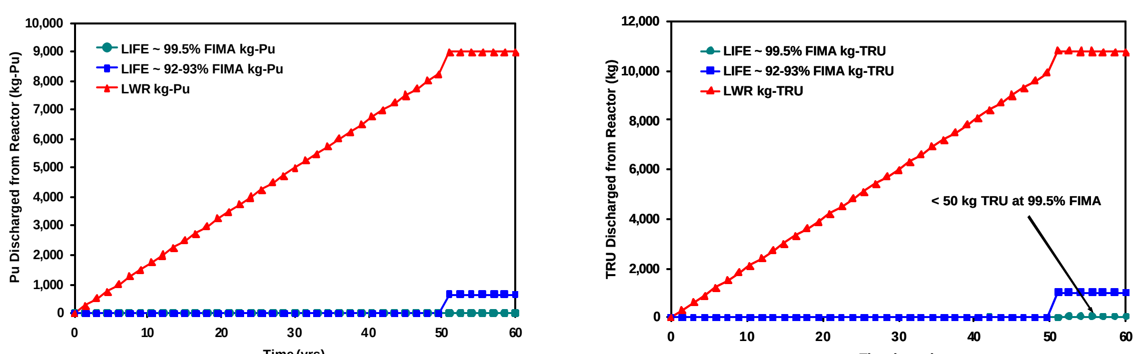
Comparison of TRU and Pu Produced by LIFE and LWR Fuel Cycles

LIFE will produce far less transuranic elements (TRU) and plutonium (Pu) for disposal than a comparable LWR. As shown in Table 7, the spent fission fuel from a DU-fueled LIFE engine will contain less than 1 kg of Pu per MT of initial heavy metal (assuming a burnup of 99% FIMA). In contrast, an LWR discharges approximately 9.9 kilograms of Pu per metric ton. Furthermore, a LIFE Engine's more efficient use of fuel promises to generate far less Pu per unit of electrical energy (GWe-net·yr) than a typical LWR (lower portion of Table 7, and Fig. 4a). The more complete burn that can be achieved with a LIFE engine will also generate less TRU (including Pu) per reactor than LWR (Table 7, Fig. 4b).

The smallest unit of LIFE fuel (a 2 cm-diameter pebble) is considered to be less attractive for theft than the smallest unit of LWR fuel (a rod, although it is difficult to remove a rod from an assembly, in practice). For example, at discharge, a representative LIFE pebble has a specific activity of approximately 21,000,000 Ci/kg-TRU, compared to a specific activity of approximately 23,000 Ci/kg-TRU for spent LWR fuel. Clearly, the LIFE fuel comes out of the engine very "hot", both thermally and radioactively. A single 2-cm pebble from a LIFE engine is a less attractive target for theft than a single LWR fuel rod (Fig. 5). The LIFE pebble contains less TRU, and is much more radioactive.

Table 7 – Actinide content of spent LIFE fuel (depleted uranium) compared with average spent LWR fuel.

	Grams element per MT of initial U at indicated burnup (% FIMA)				
Element	**80%**	**95%**	**99%**	**99.9%**	**Average LWR fuel**
U	110,000	24,000	4,500	210	960,000
Np	470	160	39	7	680
Pu	69,000	120,000	720	20	9,900
Am	7,300	1,800	170	4.4	1,200
Cm	16,000	11,000	4,400	1,000	27
Total TRU	**93,000**	**25,000**	**5,400**	**1,100**	**12,000**
	Grams element per GWe-year of energy generated at indicated burnup				
Element	**80%**	**95%**	**99%**	**99.9%**	**Average LWR fuel**
U	120,000	23,000	4,100	180	2,400,000
Np	530	150	35	6.2	17,000
Pu	79,000	11,000	650	18	250,000
Am	8,300	1,700	160	3.9	30,000
Cm	18,000	11,000	4,000	930	690
Total TRU	**110,000**	**24,000**	**4,900**	**970**	**300,000**



(a) (b)

Figure 4 – (a) Plutonium leaving each power plant as a function of time: (b) TRU (including Pu) leaving each power plant vs. time. The LIFE fuel cycle will generate less Pu and TRU per power plant than a typical LWR fuel cycle.

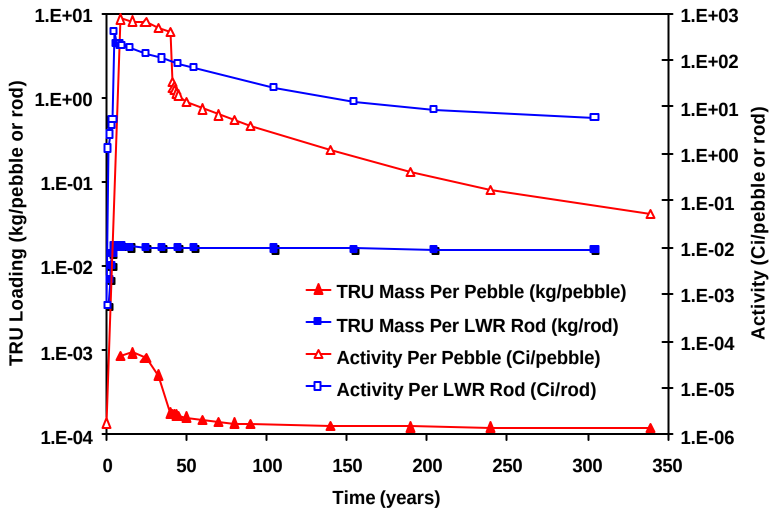


Figure 5 – Comparison of TRU mass and total activity for a single LIFE pebble and a single PWR fuel rod.

Other Alternatives to Reduce Proliferation Risk

The comparison in the preceding section pertains to the proliferation risk from a conventional LWR and from a DU-fueled LIFE engine. LIFE engines can also be designed to use TRISO particles fabricated from LWR spent nuclear fuel, to remove that fuel as a target for diversion of actinides to weapon programs. The LIFE fuel fabrication process would not involve chemical partition of the LWR spent nuclear fuel. Only mechanical processes would be needed to fabricate the LIFE fuel. These SNF-burning LIFE engines would convert most of the actinides in that spent fuel (including the ^{238}U) to fission products.

Other critical and sub-critical systems have been proposed to fission the actinides in spent nuclear fuel. Table 8 compares these options with the LIFE engine. The two LIFE engines shown in the table have relatively low mass flow (~100 kg/TWe·hr) compared to most of the other options which have several hundred to thousands of kg//TWe·hr mass flow). The LIFE engines also result in a low amount of TRU (~0.5 w/o) compared tot the other options which range from about 1 w/o to 98 w/o. Thus, LIFE appears to be able to simultaneously burn the initial charge of uranium to near completion, while producing one of the smallest heavy-metal mass flows, and lowest concentrations of transuranic elements in the waste.

The only sub-critical system (other than LIFE) in the table is known as accelerator transmutation of waste (ATW), and it is used in three ways in Table 8 (rows 12, 15, and 16). In the ATW system, reprocessing is used to separate TRU from LWR SNF for burning in a lead-bismuth-cooled reactor. In contrast, SNF can be burned in LIFE without significant isotopic enrichment or chemical reprocessing. The LIFE and ATW processes are compared in Figure 6.

Table 8 -- Comparison of Spent Fuel from LIFE and Advanced Fuel Cycles. (From Advanced Nuclear Fuel Cycles and Radioactive Waste Management, NEA No. 5990, Nuclear Energy Agency, Organization for Economic Co-Operation and Development, 2006, p. 30, Table 2.2.)

Reactor and Fuel Cycle		HM mass flow	Fuel Composition After Irradiation (Wt.% of Initial HM)					
		kg/TWe·hr	U	Np	Pu	Am	Cm	Total TRU
1	LIFE 1-GWe DU fuel (99% FIMA)	137	0.5	0.004	0.07	0.02	0.44	**0.53**
2	LIFE 2-GWe DU fuel (99% FIMA)	123	0.5	0.004	0.07	0.02	0.44	**0.53**
3	Once-through PWR (60 GWt-day/MTHM)	2050	98.5	0.10	1.35	0.08	0.01	**1.54**
4	PWR w/ Pu burning in MOX (1-pass reprocessing)	225	91.5	0.02	7.24	0.68	0.16	**8.10**
5	PWR w/ Pu+Np burning in MOX (1-pass reprocessing)	215	90.4	0.42	8.35	0.71	0.14	**9.62**
6	PWR w/ Pu burning in EU-MOX (multi-pass reprocessing)	575	89.5	0.05	9.32	0.89	0.22	**10.48**
7	PWR w/ Pu+Am burning in EU-MOX (multi-pass reprocessing)	238	91.3	0.06	7.74	0.71	0.18	**8.69**
8	PWR w/ Pu+Am burning in EU-MOX (multi-pass reprocessing)	711	92.7	0.09	6.05	0.84	0.34	**7.32**
9	DUPIC cycle (1-pass reprocessing + burning of spent PWR fuel in CANDU reactors)	1997	99	0.06	0.87	0.04	0.01	**0.98**
10	European FR (fully closed cycle)	890	77.6	0.12	21.12	0.88	0.2	**22.32**
11	PWR + Am, Pu, (Cm) burning in FR (multi-pass reprocessing)	390	78.6	0.07	20.71	0.55	0.05	**21.38**
12	Double Strata System: PWR+FR+Accelerator transmutation (fully closed cycle)	106	57.1	0.06	39.81	2.56	0.51	**42.94**
13	PWR+IFR (fully closed cycle)	289	69.8	0.65	26.6	2	0.98	**30.23**
14	Gen IV gas-cooled IFR (fully closed cycle)	849	79.3	0.15	19.48	0.87	0.24	**20.74**
15	Accelerator-driven transmutation of minor actinides	46	5.4	6.09	47.58	23.15	17.72	**94.54**
16	Accelerator-driven transmutation of TRU	117	1.9	3.29	73.48	12.37	8.96	**98.10**

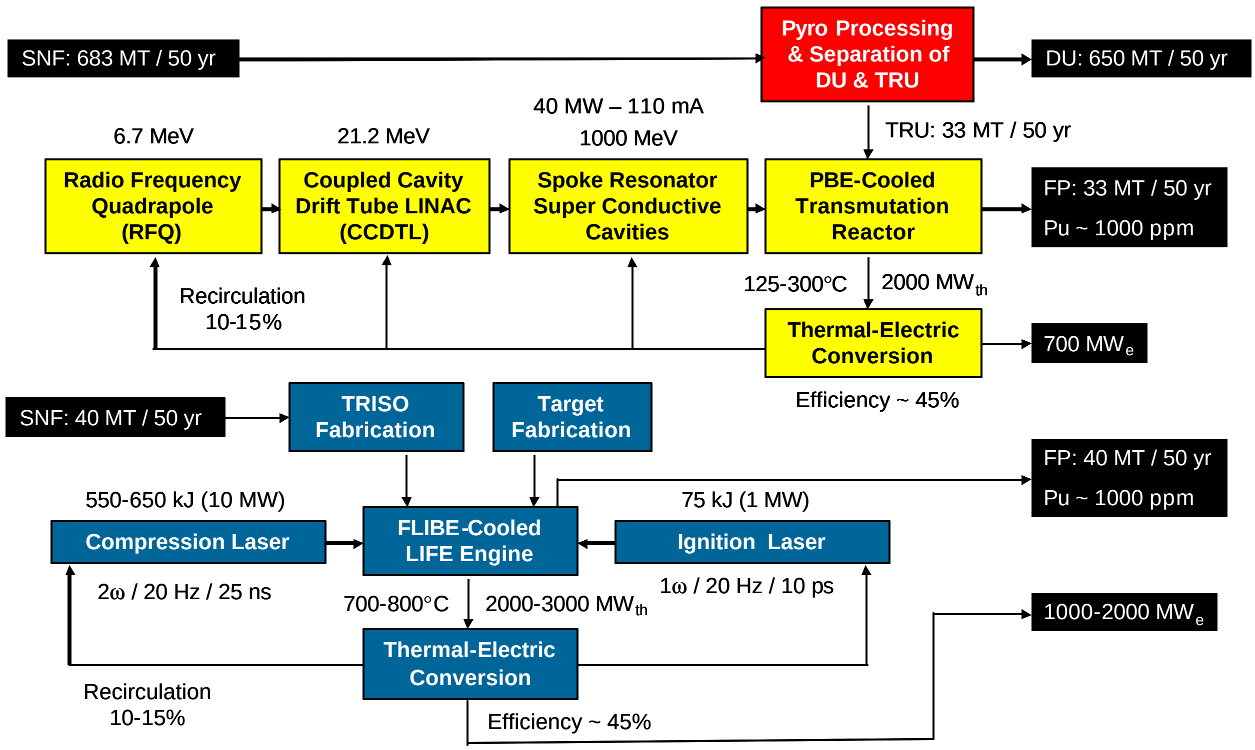


Figure 6 – Comparison of accelerator transmutation of waste (ATW) (top) and LIFE (bottom).

Thermal Power Considerations

Thermal behavior of spent LIFE fuel can be categorized into three periods: interim storage, repository preclosure, and repository postclosure.

Interim Storage Period

During the *interim storage period*, which is at least the first five years after removal from the operating LIFE engine, the thermal power from the fission product decay in the pebbles will require immersing the pebbles in a heat-transfer medium. The vessel under the LIFE engine, designed to cool the pebbles during a loss of coolant situation, could be used. If the LIFE power plant is being decommissioned, interim storage in that vessel would be appropriate. If the LIFE power plant is being refurbished with new hardware for a second generation of LIFE power production, that vessel or a similar vessel could be used at an on-site location for the interim storage.

For calculation purposes, the interim storage thermal system was conceptualized as packing the pebbles into cylindrical containers the same size as the TAD containers developed for the Yucca Mountain repository. The 40% of the volume that is between the pebbles would be filled with a static heat transfer fluid during the interim storage period. The interim storage containers (10.47 of them for a 40 MT DU LIFE engine) would be lined up in a circular conduit (with the conduit and container centerlines coincident. The conduit would be cooled with forced air ventilation, at a rate in which the air temperature would increase from 25ºC at the inlet to 60ºC at the exit of the conduit. A cooling air velocity of 1 m/s was arbitrarily chosen for the 5-year power, allowing sizing of the flow channel (4.2 m diameter). The air flow rate will be high initially, but can be reduced as the spent LIFE fuel thermal power decays. The air flow rate is calculated from the heat capacity of the air, the desired inlet and exit air temperatures, the power of the line of containers, and the surface area of the cylindrical sides of the containers. For the initial calculation, the air velocity decreased from an initial value of 12 mph to only 2 mph after 5 years.

The calculation assumes quasi-steady-state at each time (0, 1, 2, 3, 4, 5, and 10 years). The convective heat transfer, $q_{r=a}$, from the container surface (at r = a) to the air is

$$q_{r=a} = h_{air} (T_{od} - T_{air})$$

The heat transfer coefficient is taken from the Nusselt Number (Nu = h_{air} D_h / k_{air}) where D_h is the hydraulic diameter of the annulus and k_{air} is the thermal conductivity of the air. The Nusselt Number is taken from the Dittus-Boellter correlation (Nu = 0.023 $Re^{0.8}$ $Pr^{1/3}$). The Reynold's Number, Re, is [(4/p) m_{air} / (D_h μ_{air})] where m_{air} is is the air flow rate in kg/s and μ_{air} is the dynamic viscosity of air. The Prandtl Number, Pr, for air is 0.707. Conservatively using the exit temperature for the air (rather than the local temperature at the position of each container), the container surface temperature can be calculated from the heat transfer coefficient, the container power, and the surface area of the cylindrical shell of the container. Radiation to the conduit and then convection into the air or conduction to the surrounding environment is conservatively not included in this initial model.

The quasi-steady-state temperature profile across the container shell thickness and through the static fuel plus heat transfer fluid to the centerline can be calculated by combining two well-known solutions to the transport equations for heat transfer found in Theodore's book on transport phenomena (Louis Theodore, Transport Phenomena for Engineers, Energy Transport, Example 4.6.2, Long Hollow Cylinder, Example 4.6.3, Solid Cylinder with Uniform Heat Generation Rate, International Textbook Company, London, UK, 1971, pp. 157-161). The result of combining these equations is

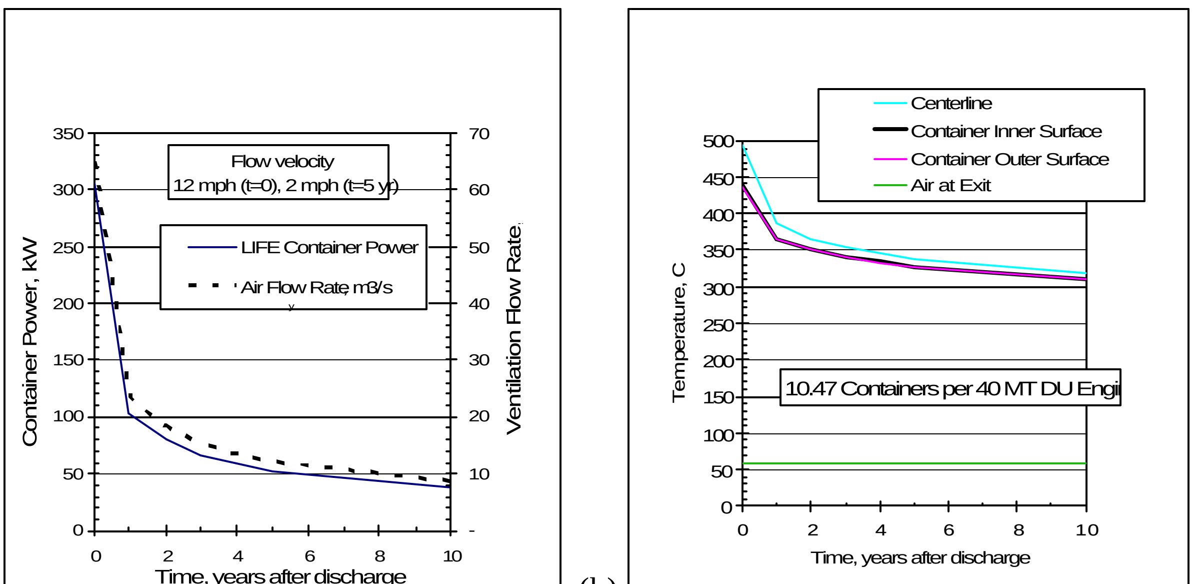
$$T_{\max} = T_{od} + \left\{ \frac{q_{r=a}}{k_{metal}} \right\} \times \left\{ a \ln\left(\frac{a}{b} \right) \right\} + \left\{ \frac{Ab^2}{4k_{fuel}} \right\}$$

The quantity $q_{r=a}$ is the heat flux on the outer surface of the container, which was calculated above from the container power and surface area, k_{metal} is the thermal conductivity of the metal container shell, A is the power density in the volume occupied by the fuel (W/m^3), k_{fuel} is the effective thermal conductivity of the fuel mass, a is the outer radius of the container, and b is the outer radius of the fuel mass (inner radius of container). Because the fuel mass consists of TRISO pebbles, with conductive filler in interstitial volumes between pebbles, the fuel thermal conductivity can be varied by selection of the static heat transfer fluid. In the model, this is accomplished by multiplying the pebble thermal conductivity by a factor, *f*. The effective fuel thermal conductivity is then calculated as:

$$k_{fuel} = f \times k^0_{fuel}$$

For the initial calculation, the static fluid was taken as having similar thermal conductivity as the pebbles, and f =1.0.

The results of the calculation are shown in Figure 7. The ventilation rate is reasonable, and will be decreased as the spent LIFE fuel decays. Peak container temperatures are below 450°C, and peak spent fuel temperatures are below 500°C. The fuel is well within its thermal limit, which will be in the 700-1400°C range, with the location in this range still being determined. The container temperature is higher than the current limit for Yucca Mountain, and hence it is likely that the interim storage container will not be a TAD that can be emptied of the static heat transfer fluid (which may not be suitable for the duration of repository performance period). Rather, at the end of interim storage, the spent LIFE fuel will be removed from the interim storage container and emplaced in a TAD, with air or inert gas filling the 40% of the container volume between the pebbles. The TAD can then be shipped to the repository, mated with a waste package, and emplaced underground.



(a) (b)

Figure 7 – (**a**) Container power and ventilation rate for interim storage of LIFE spent nuclear fuel with in a static heat transfer fluid (**b**) Temperatures at the container centerline, fuel:container interface, container surface, and air exit.

The temperature levels that would be experienced by the fuel materials during interim storage have been calculated, and indicate that with proper ventilation, the centerline of the stored spent fuel from the LIFE engine should not exceed 250 to 300°C. This temperature is well below the melting points of fuel materials, as well as the melting points of eutectics that are expected to form between silicon carbide encapsulation materials and fission products such as palladium. The Repository Design Team for LIFE continues to explore and optimize the interim storage and repository design for this hybrid fuel. The predicted power, cooling air flow, and temperature for a container filled with LIFE spent fuel during dry interim storage are shown in Figure 2. The close-packed TRISO pebbles inside the container are assumed to have an effective fractional area for thermal conduction of 0.1 (factor used to degrade thermal conductivity to account for interstitial spaces). After 100 years in such interim storage, the centerline temperature of the fuel mass should decay to a temperature corresponding roughly to the boiling point of water.

Preclosure Period in a Geologic Repository

When the spent LIFE fuel has aged 5 years, it can be placed in the repository, in waste packages filled with inert gas, and with external cooling of the waste packages by active ventilation. The ventilated period is termed the *preclosure period* for a repository.

An artist's conceptualization of the Yucca Mountain Repository design for LWR SNF is shown in Figure 8. When completed, the repository will have 108 parallel drifts with a centerline spacing of approximately 81 meters. In order to maintain the performance of the repository system, four temperature limits have been imposed on the Yucca Mountain design:

> 1) The drift wall temperature must be kept below 200°C to minimize deleterious mineral transformations and swelling.
>
> 2) The mid-pillar temperature, at a distance of 40.5 meters from the drift centerline, must be kept below 96°C to permit drainage of the percolating water through the elevation of the waste packages.
>
> 3) The container, which will be fabricated from austenitic nickel-based Alloy C-22, must be maintained below 300°C to minimize formation of deleterious (P, σ and μ) intermetallic phases that deplete the matrix of the constituents (Cr, Mo and W) responsible for the outstanding corrosion resistance of this alloy.
>
> 4) The temperature of the Zircaloy cladding of the SNF cannot exceed 350°C. For spent LIFE fuel, this limit will be replaced by a limit on the temperature of the TRISO fuel in the pebbles. That limit is still being investigated, but will likely be in the 700-1400°C range.

These four temperature limits apply to both the preclosure and postclosure periods. Because of the time constants of the heat transfer processes involved, the mid pillar temperature is the dominant limit during the postclosure period, and the other limits are more important during the preclosure period..

Five-year old spent LIFE fuel has a thermal power (per meter, when packaged in Yucca Mountain Style waste packages) that is about six times the power of the LWR waste to be emplaced in Yucca Mountain (Figures 9 and 10). The spent LWR fuel has an average age of about 23 years since discharge, and has therefore had some chance to decline in thermal output. Nevertheless, the power output of 5-year-old LIFE fuel can be accommodated by a combination of ventilation (at the 15 m^3/s rate per disposal drift of Yucca Mountain) and phased emplacement in the repository drifts. In phased emplacement, twenty-one waste packages from two LIFE engines would be emplaced each decade, filling a drift in five such phases over a period of 50 years. For a higher-volume waste stream, the repository operator would fill multiple drifts simultaneously, maintaining a 10-year in-drift cooling period between phases for each drift.

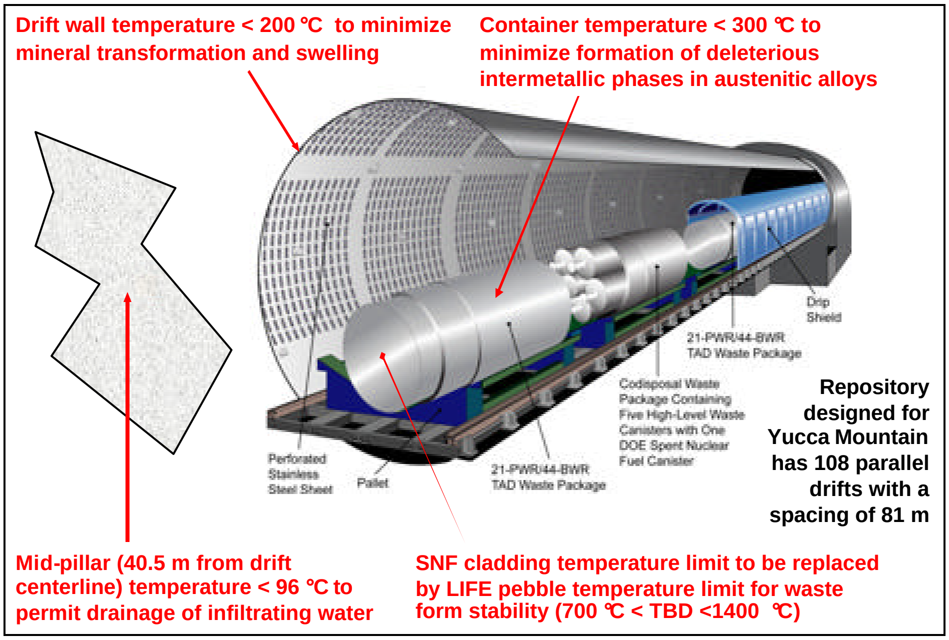


Figure 8 – Artist's conceptualization of the Yucca Mountain repository showing various temperature limits for its operation.

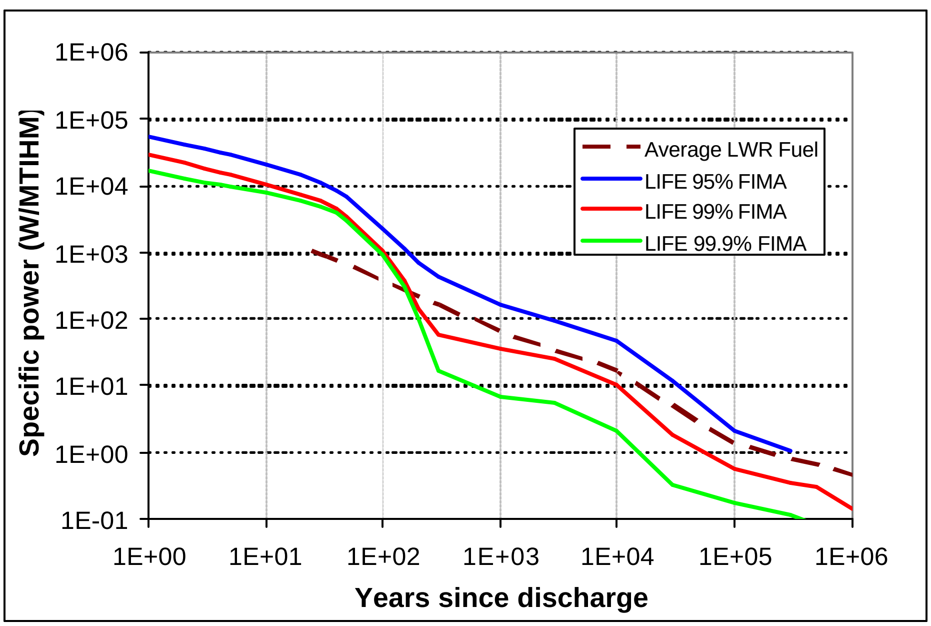


Figure 9 – The thermal power of spent fission fuel from LIFE Engine compared with spent LWR fuel as a function of time. Three burn-up conditions are assumed for the LIFE fuel, corresponding to 95%, 99% and 99.9% FIMA. After a few hundred years, the thermal power of both LWR fuel and LIFE fuel is dominated by the decay of the actinides. The differences in the thermal powers of LIFE fuels with different burnups are a reflection of the decreasing actinide content of the fuel as burnup increases.

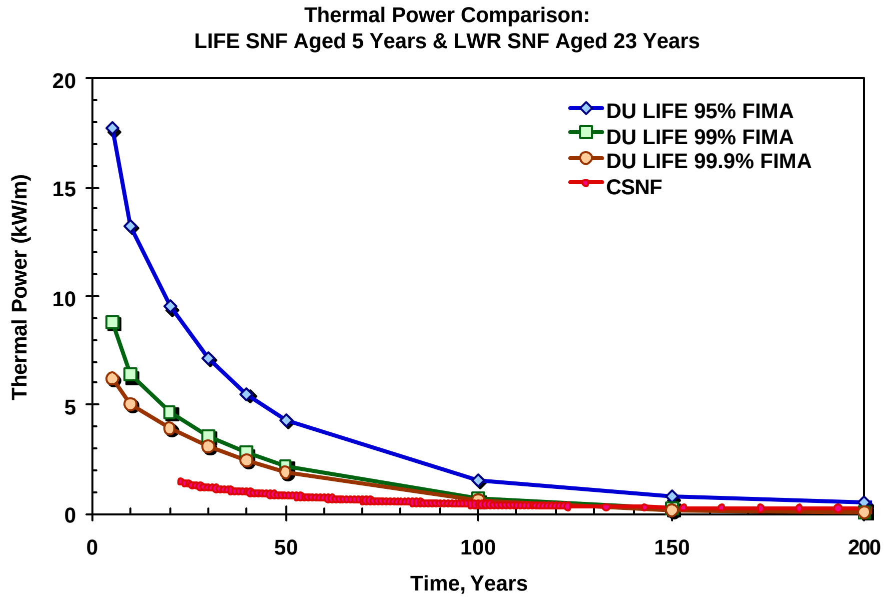


Figure 10 – The thermal power of LIFE SNF at 95, 99 and 99.9% FIMA compared to that of a typical commercial LWR SNF.

The ventilation model for Yucca Mountain was adapted for phased emplacement. The ventilation model [Ref *D*] includes thermal radiation from the surface of the waste package to the drift wall, convection to the ventilation air from the surfaces of the waste package and the drift wall, and conduction within the rock mass surrounding the emplacement drift. These processes were modeled using analytical techniques that assume quasi-steady-state at each time step, a series of well-mixed volume elements along the repository drift, and the principle of superposition to calculate the temperature response of the rock mass due to a heat flux. The use of the quasi-steady-state approximation allows the energy balance equations to be written without time derivatives, resulting in algebraic solutions to the various components of the thermal energy balance. The progress of the calculation through time is like that of integrating a function using Euler's method of numerical integration, summing a "stair-step" approximation. The drift is divided along its length into volumetric elements, and the properties are assumed to be well-mixed in each volume element such that the variables of interest (*i.e.*, temperature) are the everywhere the same within the element. Application of the superposition technique for the heat transfer within the surrounding rock mass is based on scaling and time-shifting of a single temperature response of the drift wall to a short-duration constant flux. The single temperature response is the higher of the temperature increases for two analytical solutions [Ref *E*]: for a region bounded internally by a circular cylinder and for the semi-infinite slab (the cylinder solution is higher for the first twenty years). The single temperature response is scaled using the heat flux from the waste package at the time of interest, and the response is combined with the responses for the prior time steps. A convective heat transfer coefficient of 5.7 W/m^2K, indicative of mixed natural and forced convection, is used in the model. Both the natural and forced convection components of the heat transfer fall within their respective turbulent regimes.

Figure 11 shows the results of the thermal calculation. The location for this graph is near the air exit of the drift, which is the hottest end. Peak emplacement drift (tunnel) wall temperatures under *normal preclosure operations* would be at least 25°C below the 200°C limit imposed by mineral stability of Yucca Mountain tuff. Peak waste package surface temperatures are at least 100°C below the 300°C limit imposed by phase stability of the nickel-based alloy (C-22) used as the corrosion-resistant outer shell of the waste package.

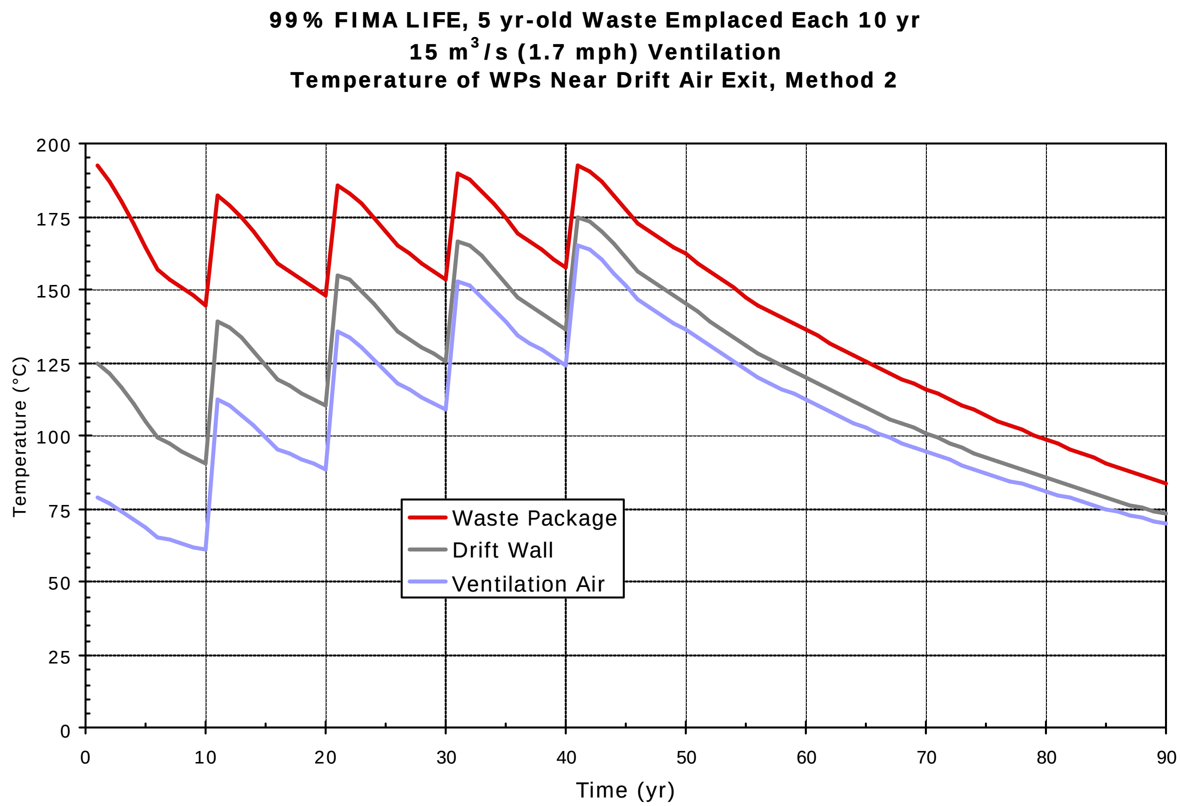


Figure 11 – Temperature of LIFE waste packages, the drift wall, and the ventilation air, for the waste package nearest the air exit, which is the hottest waste package.

A model similar to the interim storage model described above was developed for the pebble temperatures. However, because the pebbles have a small contact area with each other, radiation between pebbles will also contribute to the heat transfer. Natural convection of the air in the 40% of the volume of the TAD that is between the pebbles is another potential heat transfer mode. The model developed for initial calculations consists of a series of 2-cm-thick cylindrical annuli composed of the pebble material. The annuli are separated by narrow gaps across which radiation must carry the heat. Once the centerline and surface temperatures were calculated from this model (at each selected time for the quasi-steady-state calculation), a bounding natural convection model was used to determine that natural convection cannot carry a significant fraction of the heat flux from the centerline to the inside surface of the TAD.

The results of the pebble temperature model are shown in Figure 12, based on a boundary condition of 200ºC at the TAD inner surface. Peak pebble temperatures are about 915°C. The temperature limit for the pebbles has not been finalized; however, it is likely to be between 700 and 1400°C. If the pebble temperature limit is at the low end of this range, interim storage of spent LIFE fuel would need to be extended to about 25 yr, similar to the *de-facto* operational scenario for LWR waste in Yucca Mountain. Alternatively, the ventilation rate could be increased, and/or a conductive filler could be added to the waste packages.

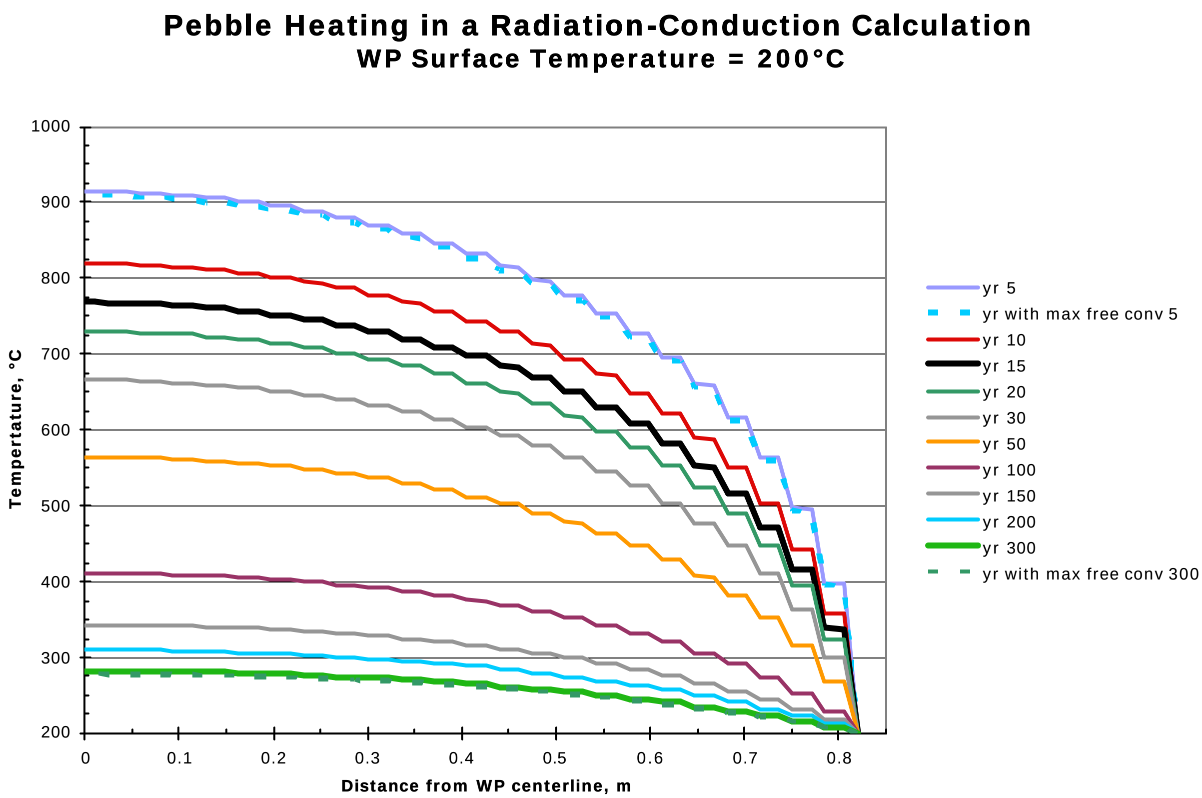


Figure 12 – Temperature of the interior of a LIFE waste package for normal operations during the preclosure period.

Most *off-normal repository events* (flooding, high-magnitude earthquakes, volcanism, meteor impact) are of sufficiently low probability that they can be screened out of the safety analysis. The most significant off-normal repository event to be considered for the preclosure period is a loss of ventilation power. The thermal time constants for the repository are sufficiently long that a loss of ventilation can be tolerated for over a month for the existing Yucca Mountain scenario. Because of the higher thermal power of young spent LIFE fuel, the allowable period of non-ventilation will be shorter than for 23-yr-old LWR waste. If appropriate, the LIFE repository design would include emergency generators and redundancy for the ventilation fans to ensure the waste package temperature will not exceed the 300°C limit for a significant period.

The model developed for normal operations is suitable to calculate WP interior temperatures during off normal situations, by simply changing the boundary condition at the inside surface of the TAD (it should be noted that the temperature at the inside surface of the TAD is within a few degrees of the outside surface of the waste package due to the high thermal conductivity of the

TAD and two waste package layers. The results of the off-normal calculation are shown in Figure 13. The peak pebble temperature is about 925°C. For a pebble temperature limit at the low end of the 700 to 1400°C range, the limit would not be exceeded if the ventilation loss occurred after the age of the spent LIFE waste reached 28 yr. For a pebble temperature limit above ~900°C, even young (5-yr-old) spent LIFE fuel would not exceed the limit if the waste package surface temperature does not exceed 300°C. A longer interim storage period or additional ventilation capacity and redundancy could be used if the pebble temperature limit is at the low end of the potential range.

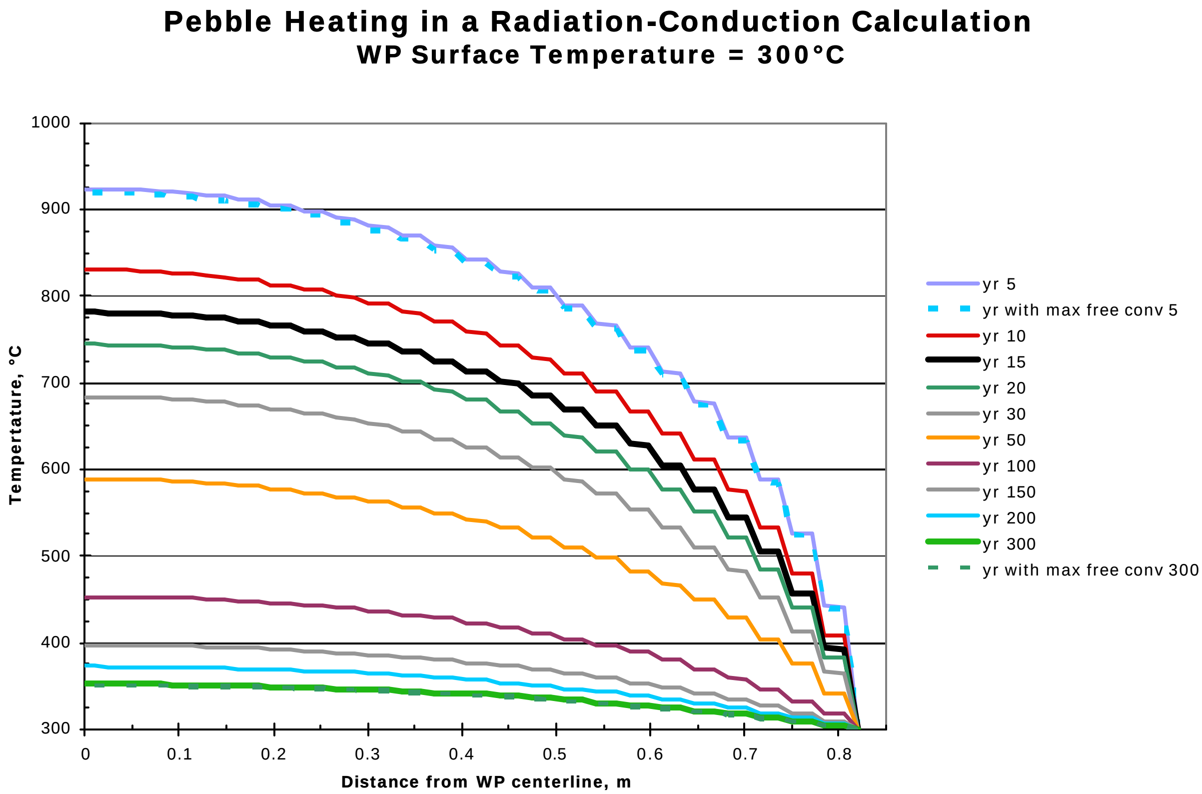


Figure 13 – Temperature of the interior of a LIFE waste package for off-normal operations during the preclosure period.

Postclosure Period in a Geologic Repository

Postclosure thermal performance of the repository relies solely on the heat sink of the repository rock (and ultimately of the mountain surface and water table). At about 115 yr age, spent LIFE fuel and LWR waste have the same thermal power (per meter, in Yucca-Mountain-style waste packages). After that time, spent LIFE fuel requires less cooling than LWR waste to stay within the four repository thermal limits. The pebble, waste package surface, and drift wall limits have been discussed above; the mid-pillar (midway between the repository emplacement drifts) temperature is the remaining limit, and is the controlling limit for postclosure thermal performance. To avoid impeding drainage of percolating water through the repository horizon, the mid-pillar temperature should not exceed the boiling point of water (96°C at the repository elevation) for significant periods of time (and for extended lengths of the mid-pillar). At Yucca Mountain and for LWR waste, the mid-pillar temperature reaches ~70°C about a century after repository closure (waste age ~175 yr), and peaks near the boiling point of water about five centuries after repository closure. Because most (80-90%) of the preclosure thermal power spent LIFE fuel will be removed from the repository by the ventilation air, it is the postclosure thermal power that will drive the temperature history at the mid-pillar. The spent LIFE fuel thermal power will be less than that of LWR waste almost immediately after closure; therefore, it is not expected that the mid-pillar temperatures in a LIFE repository will exceed those in a Yucca Mountain LWR repository.

Conclusions

The fusion-fission LIFE engine concept provides a path to a sustainable energy future based on safe, carbon-free nuclear power with minimal nuclear waste. The LIFE design ultimately offers many advantages over current and proposed nuclear energy technologies and could well lead to a true worldwide nuclear energy renaissance. When compared with existing and other proposed future nuclear reactor designs, the LIFE engine exceeds alternatives in the most important measures of proliferation resistance and waste minimization. The engine needs no refueling during its lifetime. It requires no removal of fuel or fissile material generated in the LIFE engine. It leaves no weapons-attractive material at the end of life.

Although there is certainly a need for additional work, all indications are that the back end" of the fuel cycle does not to raise any "showstopper" issues for LIFE. Indeed, the LIFE concept has numerous benefits:

- Per unit of electricity generated, LIFE engines would generate approximately 15 times less waste (in terms of mass) requiring disposal in a HLW repository than does the current once-through fuel cycle.
- Although there may be advanced fuel cycles that can compete with LIFE's low mass flow of heavy metal, all such systems require reprocessing, with attendant proliferation concerns; LIFE engines can do this without enrichment or reprocessing. Moreover, none of the advanced fuel cycles can match the low transuranic content of LIFE waste.
- The specific thermal power of LIFE waste is initially higher than that of spent LWR fuel. Nevertheless, this higher thermal load can be managed using appropriate engineering features during an interim storage period, and could be accommodated in a Yucca-Mountain-like repository by appropriate "staging" of the emplacement of waste packages during the operational period of the repository. The planned ventilation rates for Yucca Mountain would be sufficient for LIFE waste to meet the thermal constraints of the repository design.
- A simple, but arguably conservative, estimate for the dose from a repository containing 63,000 MT of spent LIFE fuel would have similar performance to the currently planned Yucca Mountain Repository. This indicates that a properly designed "LIFE Repository" would almost certainly meet the proposed Nuclear Regulatory Commission standards for

dose to individuals, even though the waste in such a repository would have produced ~15 times more generated electricity than the reference case. The societal risk/benefit ratio for a LIFE repository would therefore be significantly better than for currently planned repositories for LWR fuel.